TESTING ARTIFICIAL INTELLIGENCE APPLICATIONS FOR SATELLITE COMMAND AND CONTROL

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Abstract

This paper addresses a concept for the test and evaluation of automation, robotics and machine intelligence (commonly referred to as artificial intelligence (AI)) for command and control of space systems. Using AI to reduce mission operations costs has been proposed and implemented (although sparsely) over the past twenty years, but has never been fully accepted by satellite operators or project managers. Several reasons for this "non-acceptance" exist, but one reason is seen as being paramount. The risk factor in using AI tools is much too high. The space industry routinely tests spacecraft hardware and software to reduce risk, and has invested significant capital developing special facilites to certify that a spacecraft is mission ready. Until now, no such facility was available for testing AI tools and applications, until the development of the Spacecraft Artificial Intelligence Laboratory (SAIL). SAIL is implementing a capability to test AI tools on a fully functional, on-orbit spacecraft. Since the test spacecraft was the first flight in a constellation of ten, an operational baseline is being established by human operators controlling the remaining nine spacecraft. Validation of AI applications will be accomplished by measuring an AI tool's performance against the operational baseline.

Introduction

Ten years ago the Goddard Space Flight Center (GSFC) hosted a conference on artificial intelligence. One of the goals of this conference was to promote the utilization of AI technology in spacecraft and experiment command and control, and mission planning systems. Numerous technical papers were presented (most of which addressed the use of expert systems), which provided a vision of the future for satellite operations. However, very few, if any of these ideas made it into the operational environment. Today, there is not a single satellite commanded and controlled out of GSFC that does not require substantial human intervention, so it could be easily argued that AI has had minimal impact over the past ten years on space system mission operations.

Background

Ref. 1 states that the "major elements of mission operations are a team of operators to command and control the spacecraft bus and its payload, planners to translate requirements into operational activities, and a staff of engineers to keep the spacecraft healthy and meeting the data users' needs". It is certainly reasonable to expect the consistent reference to human operators in the above explanation for mission operations, especially since automation and machine intelligence has been used so sparingly on operational space systems. It is also reasonable to expect that when mission operations functions have been automated, the focus has been on the operators that command and control the spacecraft bus and its payload. However, as shown above, there are three major elements of mission operations and to achieve the lofty goal of a totally automated mission control center, all functions of the major elements will have to be automated. Considering that AI tools (like humans) perform some tasks well, and others not so well, our concept is to develop individual AI software applications to accomplish specific functions and then integrate them into the overall ground system software.

Generic Functional Elements (GFE) of Mission Operations

Space systems perform a variety of missions, including communications, navigation, Earth observation, etc., and these missions are carried out with widely varying levels of sophistication. The same can be said regarding the on-orbit platforms used to execute these missions. Spacecraft, or constellations of spacecraft vary widely in their designs, from small communications satellites designed to store and forward electronic messages to massive, orbital observatories. Although the types of missions and sophistication of spacecraft designs vary, the functions required to execute the missions and maintain a spacecraft's health and status are relatively generic. Ref. 1 has defined the major elements of mission operations as; (1) Mission Planning, (2) Personnel Training, (3) Spacecraft Operations and (4) Engineering Support. The focus of this paper is concerned with automating mission operations functions with artificial intelligence, therefore, personnel training will not be addressed here.

Mission Planning - includes such generic functions as scheduling ground station support, generating command files, generating ephemeris and star loads, managing short term resources and supporting short fuse requirements, such as observing targets of opportunity.

Spacecraft Operations - typical functions include commanding the spacecraft, monitoring subsystems, managing payloads, managing data recording devices, recovering payload data and resolving minor anomalies with relatively short fuses.

Engineering Support - includes such functions as maneuver planning, managing subsystems, managing long term resources, resolving major anomalies, and analyzing spacecraft trends

"Market Pressures"

Why now? With a good track record of operating space systems for over thirty years with minimal failures, why are so many space industry professionals now calling for computers to do what humans have done so effectively in the past. To borrow a phrase from the economic community, we are responding to the pressures of todays market.

Reduced Budgets

Both the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA) have experienced considerable reductions in their operating budgets over the past five years, as have many aerospace companies competing in the commercial sector. With today's fiscal constraints and tomorrow's projected budgets, it is totally unacceptable for mission operations to account for a major portion of a space system's life cycle costs.

Smaller Organizations

Organizations are managing differently, giving employees greater control over their "professional destinies" and eliminating layers of management. The focus on quality and teamwork has led to the elimination of redundancy and duplication of effort, allowing greater levels of productivity to be achieved. Future mission operations staffs will be forced to be smaller because there will be a smaller pool of talent to draw from within an organization.

Greater Demand

With the explosion of personal communication devices (PCDs), greater reliance on space-based navigation systems and recent availability of high resolution imagery from space, the demand for satellite services has never been greater. We now operate constellations of spacecraft that number in the twenties, e. g., the Global Positioning System, and a future PCD program is projecting that it will have over sixty satellites in its constellation. Operating sixty satellites using today's manpower models would demand huge operational staffs, a luxury that will not be affordable if the PCD business is to be cost effective.

Increased Number of Data Points

As spacecraft and telecommunication links have become more sophisticated, the number of telemetry points has also dramatically increased. Monitoring of real-time telemetry by human operators for a spacecraft with over 10,000 telemetry points would, for all practical purposes, be close to impossible and future trends are even more staggering. Scanning mnemonics on a page and mentally analyzing trends of individual telemetry parameters are rapidly becoming unwieldy tools in modern space system mission operations.

Corporate Knowledge

The Hubble Space Telescope (HST) has a mission lifetime of fifteen years. The operations team for that project was originally assembled at Goddard Space Flight Center in 1982. HST was launched in 1990, so its expected operational lifetime will extend until 2005. If one of the original members of the mission operations team stayed on the HST project until it was terminated, he or she would have spent approximately 23 years of their career on this single project. Realizing that that scenario is unrealistic, project managers will have to accept the fact that each time a personnel change takes place in today's environment, some corporate knowledge will be lost in the process. The cause for concern here is that by the time HST is in its final year of operation and functioning with non-redundant systems, will sufficient corporate knowledge remain to keep that spacecraft reliably producing high quality science data?

Changing the Culture

As discussed, AI applications have been considered for command and control of space systems for at least ten years. Why then has there been so little movement in that direction? Part of the reason is cultural; if something works, why change it! Secondly, on the majority of space project new starts there have been no specific requirements articulated which demand the use of automation or machine intelligence for mission operations.

The Human Element

Because human beings are extremely flexible and have the ingenuity to deal with partial information and novel situations, there are instances when human involvement is absolutely necessary, however, that does not infer that people are required all of the time. Aircraft pilots fondly describe flying as "hours and hours of sheer boredom, punctuated by moments of stark terror". The same can be said for spacecraft operations, except the hour factor is more akin to days. Just as the aviation industry has automated flight control systems, the space industry needs to automate routine, recurring satellite operations functions.

Humans are low risk, but high cost. It is a given that humans can operate spacecraft and do it exceedingly well. However, highly trained engineers and scientists are cost prohibitive in a fiscally constrained environment and their talents can be better utilized designing the future instead of serving the present, or past. The only way to alleviate these highly trained specialists from performing routine tasks is through the use of automation.

Automation and Machine Intelligence

Neural networks, fuzzy logic, case-based reasoning, state modeling, and expert systems are all examples of automation and machine intelligence. Expert systems have been used operationally for monitoring of spacecraft subsystems, as has state modeling. Case-based and model-based reasoning have been used to schedule ground system support. All have been moderately successful. Why then have space system operators, engineers and project managers been so reluctant to use other AI tools to perform alternate mission operations functions?

High Risk - although most software applications are relatively inexpensive to operate (versus humans), their utilization is so risky that project managers are unwilling to accept their use for command and control. The possibility that an AI tool would send the wrong command(s) to a spacecraft completely crippling it, far outweighs the added expense of using lower risk human beings.

Testing and Validation

Spacecraft manufacturers put their hardware and software through exhaustive tests to reduce the risk that a spacecraft will not function as designed once on orbit. These tests are extremely costly, often requiring special facilities and test apparatus (anechoic, vacuum and thermal chambers, vibration appratus, specially designed aircraft) to simulate the space environment. But once complete, project managers are relatively certain that the risk of launching a non-functional spacecraft is at an acceptable level. This process is usually dubbed "space qualification" by integration and test personnel.

Hardware Testing

Typically, spacecraft flight hardware is rigorously tested in an environment as close as possible to what it will experience while on orbit. Considering that we can never fully replicate the space environment (due to the inability to simulate a near total vacuum and micro-gravity conditions at the same time), these tests only marginally prove the functionality of a spacecraft's systems. Due to the operational flexibility provided by the Space Shuttle, a program was initiated to test flight hardware in the orbiter's cargo bay, thereby providing the most accurate tests possible and providing a true "space qualification" of flight hardware. For example, crew aids and tools manifested for use on the first servicing mission of the Hubble Space Telescope were tested on a Space Shuttle mission (STS-51) several months prior to the actual repair mission.

Software Testing

Ground system software is thoroughly tested as well, and in some cases, by an independent organization. However, this testing is usually executed using a satellite simulator, especially if the ground system software is written to command and control only a single satellite. Although acceptable, using a satellite simulator to verify software performance does not provide the fidelity that tests would if they were conducted using an on-orbit spacecraft.

Testing of a space mission's ground system software using a satellite simulator is acceptable to project managers due to the fact that in the majority of cases it is the only means available and once the real spacecraft is on orbit, you have humans in the command and control loop. However, using a satellite simulator to test an AI application which replaces humans in the loop is extremely risky and unacceptable to most project managers. The challenge then is to find a suitable on-orbit spacecraft to test AI applications, and measure the AI tools performance against an established operational baseline.

The Spacecraft Artificial Intelligence Laboratory (SAIL)

SAIL is a joint Navy / NASA / Industry / Academia research and development project which uses existing facilities at the U.S. Naval Academy (USNA) to test and evaluate AI applications and techniques for command and control of space systems. The SAIL project is unique because it uses the UHF Follow-On (UFO) Flight #1 spacecraft as an on-orbit test bed, providing the means to "space qualify" AI applications for satellite command and control. Additionally, since there will be a total of ten UFO spacecraft (UFO-1 through UFO-10) on orbit once the entire constellation is launched, an operational baseline is being established by USAF & USN satellite controllers who are currently providing telemetry, tracking and command (TT&C) of those satellites.

On-Orbit Test Article

UFO flight #1 was launched on 23 March, 1993. Due to an anomaly experienced with the launch vehicle, the spacecraft was unable to achieve geosynchronous orbit with the specified fuel reserve to support a useful 14 year mission. It was deemed non-operational by the U.S. Navy and boosted out to a super-synchoronous orbit. The spacecraft is currently in a near circular, 22,925 Nm, 26.055^{o} inclination orbit and has a 24 hour, 11 minute orbital period. On average, the spacecraft is visible for approximately a 45 day interval from the Naval Academy ground station.

The UFO satellite is based on the Hughes product line of HS601 spacecraft and is a modular bolt-together structure. It is a body-stabilized geosynchronous communications satellite in the UHF communications band and has five major subsystems: Structural, Telemetry and Command, Propulsion, Attitude Control, and Power.

Interface with the ground is via the telemetry and command (T&C) subsystem. The ground uplink commands via S-BAND Space to Ground Link Segment (SGLS) channel 11 or 13. The uplink is encrypted (the encryption system can be commanded off from the ground if required) and is nominally transmitted at 1000 bits/second (bps).

Ground Station

Most operational control centers that provide TT&C for space systems are totally dedicated to their specific missions. If command and control assets are not being used to support real-time operations, then they are usually employed conducting simulations or on-the-job training. Additionally, the space-based asset of a typical project is usually 100% dedicated to performing its mission, therefore, little time is ever devoted to improving the command and control process or reducing mission operations costs. With an on-orbit test bed available, the challenge was to find a suitable ground station that was flexible enough to execute the test and evaluation mision in conjunction with its other missions.

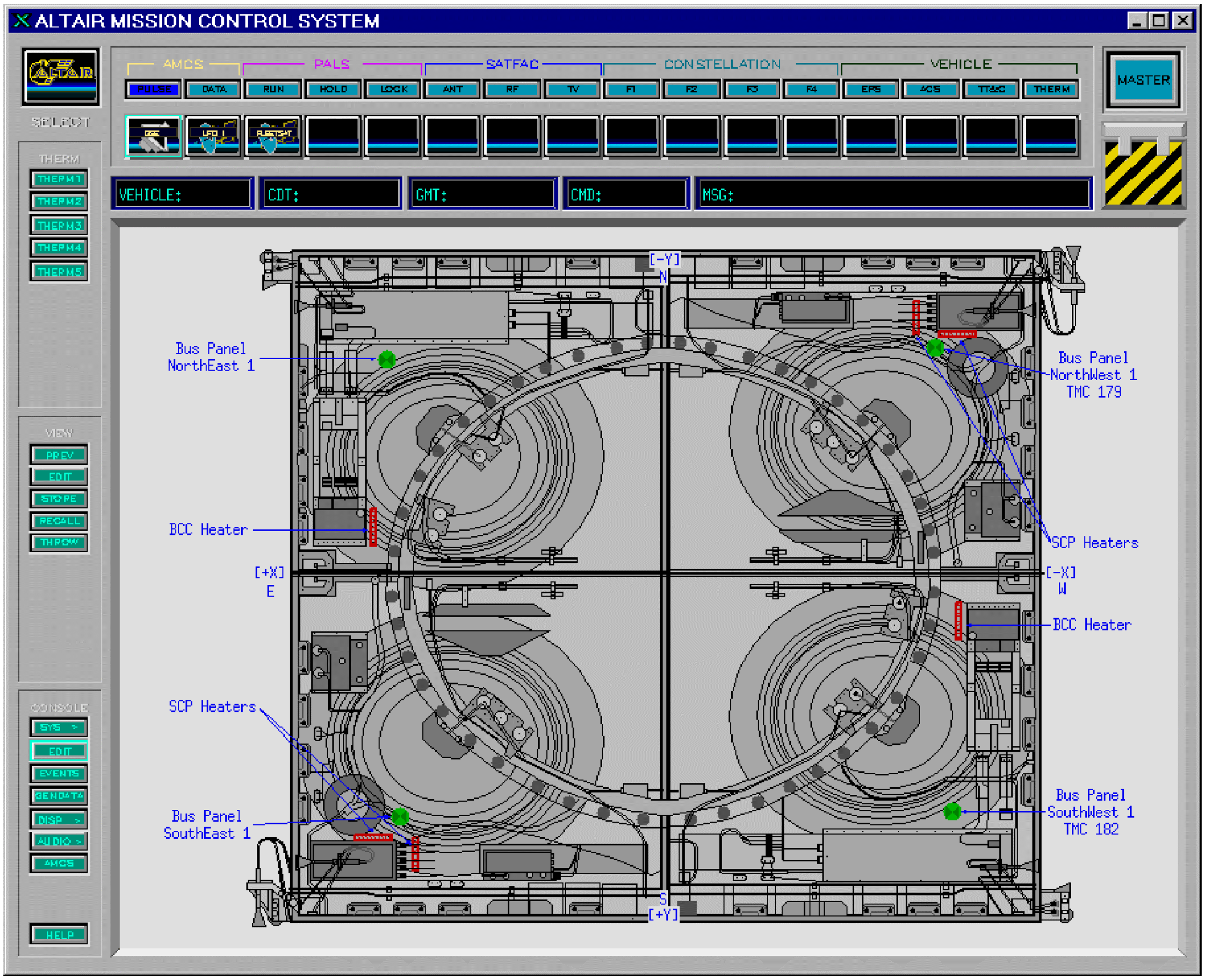
The Naval Academy's satellite ground station and communications center has been in operation and under continual development since 1988. The facility has a twofold purpose:

(1) to provide laboratory facilities in support of the mission of the Academy and
(2) to provide a research and development facility in support of the Navy.

Consequently, the facility is deliberately designed to be highly versatile and easily adaptable to any type of space mission. Since the USNA ground station does not currently support an operational space system, the facility has the flexibility to support continuous testing with the UFO-1 spacecraft when it is in view of the ground station.

Ground System Software

Due to the type of testing that the SAIL project is to perform, it was decided to provide a "visual window" into the UFO-1 satellite's operational status. This was accomplished by using two Commercial Off-the Shelf (COTS) software packages. The Altair Mission Control System software (developed by Altair Aerospace) provides the ability to monitor subsystems by using dynamic, two dimensional displays of UFO-1 telemetry. Satellite Tool Kit (developed by Analytical



UFO-1 THERMAL SUBSYSTEM GRAPHICAL DISPLAY

Graphics, Inc) is being used to display a three dimensional model of UFO-1 in its proper orbit and attitude, and is also updated using real-time UFO-1 telemetry and ephemeris data. The reasoning behind our "visual window" approach was prompted by the use of AI tools in the command and control loop. In case an AI tool malfunctions, the UFO-1 operations team will have the ability to rapidly assess what the spacecraft is doing to ensure that no damage is done to UFO-1.

UFO Block I Satellite Simulator

The Navy Satellite Opertions Center has a UFO Block I satellite simulator which is currently used for operaor training and validation of ground system software. The SAIL project will use this simulator to verify and validate our ground system software and also to test the reponses of AI tools under normal and anomalous operating conditions.

Developing Trends In AI Tool Design

Since project inception in August of 1995, SAIL team members have interfaced with numerous organizations which are currently producing AI applications for satellite command and control. An obvious trend that has become apparent regarding the development of these AI applications is that they are being designed to perform a particular mission operations function. For example, engineers from the Office of Advanced Concepts and Technology at NASA's Jet Propulsion Laboratory have developed an AI tool (SELMON) for detecting and isolating abnormalities in spacecraft sensor data (Generic Functional Element - monitoring subsystems).

Engineers from the Flight Dynamics Division at Goddard Space Flight Center are currently producing an automated maneuver planing tool which uses fuzzy logic to perform routine orbit maintenance ((Generic Functional Element - maneuver planning). With the advent of stand-alone AI applications that perform specific mission operations functions, is it now possible (and preferable) to perform certain mission operations functions using modular AI applications?

<u>Modular Software Packages</u>

A perfect analogy to describe this concept of modularity in satellite mission operations are the commercial "office" software packages. These packages provide personal computer users with integrated applications which perform specific functions required to run an office. For instance, one popular package provides an application for word processing, an application for telecommunications, a database application, a spreadsheet application, a graphics application and a project management tool, all integrated so that information is readily shared between the applications. The same paradigm can be used for integrating AI applications into satellite ground systems. Standalone AI applications could be integrated into a specific space mission's ground system, which would serve as the medium through which the modular applications passed and shared data. The standalone capability would be achieved by rigorously testing each AI application and verifying its capabilities by using established metrics based on human performance.

This concept of modularity would provide project managers with greater flexibility than currently exists in executing mission operations. Depending on the level of sophistication of either the spacecraft or its mission (as well as available operations funds), AI tools could be combined together to totally automate mission operations or used in conjunction with humans to partially reduce manning levels. The degree of implementation would be dependent only on the level of risk that a particular project manager was willing to accept.

Conclusion

The demand for satellite services will continue to increase in the near future, requiring more sophisticated spacecraft and missions to meet the demand. As spacecraft on-orbit time increases, so does the percentage of operations cost to total life cycle cost. The present mission operations culture is heavily dependent on human involvement to safely execute space missions, which adds to the cost of doing business in space.

The obvious solution to reducing mission operations costs is through the judicious use of automation, machine intelligence and robotics, however, these tools must be thoroughly tested and verified before project managers will be satisfied that their use is not too risky.

A facility dedicated to the test and evaluation of artificial intelligence tools and applications for satellite command and control, which uses on-orbit spacecraft as test beds will reduce the risk of using AI products in the operational environment.

References

[1]Larson, W.J. and Wertz, J. R., *Space Mission Analysis and Design*, Microcosm, Inc., Torrance, CA, 1992